Home-brewed circuits tailor sensor outputs to specialized needs

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No off-the-shelf pretrimmed sensor right for your job? No problem; use an untrimmed unit and customize it with a signal conditioner based on two or three op amps. These analyses show you why the design job is no big deal.

Although you can buy fully signal-conditioned, calibrated, and temperature-compensated monolithic sensor ICs, you're often better off designing your own signal-conditioning circuits. Two cases arise frequently: You're building a prototype, and you need to rapidly modify the transfer function of a sensor/amplifier subsystem, or you can't buy exactly the transfer function you need in a fully signal-conditioned, precision-trimmed sensor. (Maybe the signal-conditioned device is trimmed over a pressure range different from the one you need.) In such cases, there will always be a place for low-level, non-signal-conditioned sensors. Whenever you use such sensors, you need sensor-interface amplifier circuits to condition the "raw" sensor outputs to usable levels. Such circuits should be simple, cost-effective, and easily modified to suit a variety of applications.

Today's unamplified solid-state sensors usually have output voltages of tens of millivolts. (When powered from a 5V supply, Motorola's basic 10-kPa pressure sensor, the MPX10, has a typical output of 58 mV.) Therefore, you need gain to obtain a signal large enough for additional processing. Examples of additional processing are digitization by a microcontroller's A/D converter and limit sensing by a comparator. Although this article describes signal-conditioning circuits that work with almost any low-level, differential-voltage-output sensor, it focuses on amplifiers for pressure sensors.

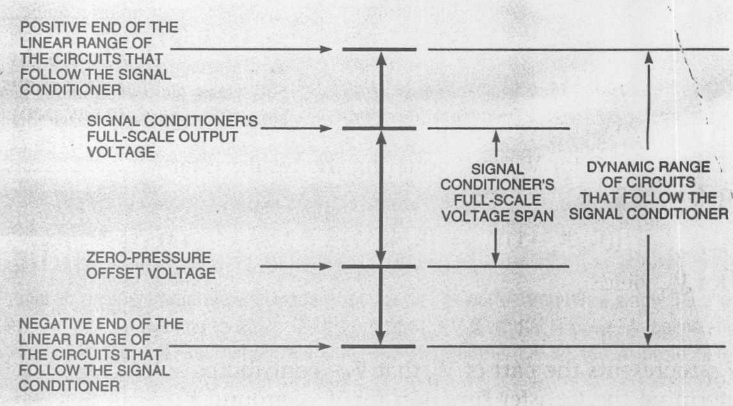
This article presents a basic two-op-amp signal-conditioning circuit that exhibits instrumentation-amplifier characteristics:

- high input impedance
- low output impedance
- differential-to-single-ended conversion of the pressure-sensor signal
- high-gain capability

A couple of modifications to this two-op-amp circuit allow gain adjustment without compromising common-mode rejection ratio (CMRR) and both positive and negative dc-level shifts of the zero-pressure offset. Variable gain and offset are desirable because pressure sensors' full-scale span and zero-pressure offset vary somewhat from unit to unit. With variable gain you can fine-tune the sensor's full-scale span. Offsetting a pressure-sensor signal lets you translate the signal-conditioned output span to a specific level (for example, to make the full pressure range of interest lie within an ADC's input range).

The following describes derivations of the two-op-amp gain stage's transfer function and a simplified transfer func-

FIGURE 1



By offsetting the amplified sensor output, a signal conditioner can bring the full signal range of interest within the following circuits' input range.

tion for pressure-sensor applications. You'll also learn how to make the gain adjustable and how to provide variable dc offset. With a third op amp, you can produce a negative shift in the signal conditioner's output voltage. You must reduce the gain of the two-op-amp stage to compensate for the additional gain the third op amp provides. The following material includes a derivation of the gain expressions for the three-op-amp circuit and an explanation of how to introduce a negative offset.

A pressure-sensor interface circuit often must offset its output voltage upward or downward. Offset can come in handy if a signal that represents a pressure of interest falls below the bottom of the signal conditioner's linear range or the linear range of an ADC or op-amp circuit following the signal conditioner. In such cases, your system cannot distinguish between the applied signal and a larger one just at the edge of the range. For similar reasons, you may want to add an offset to assure that the signal-conditioner output corresponding to the highest pressure of interest does not exceed the top of the range (**Fig 1**). Offsets can't always bring signals within range or the amplifier's high and low saturation rails, though; if the difference between the highest and lowest conditioned outputs exceeds the range of the signal conditioner or the circuits that follow it, you have to reduce the signal conditioner's gain or attenuate its output.

The two-op-amp gain stage's transfer function

You can determine the transfer function of **Fig 2**'s two-op-amp signal-conditioning stage using nodal analysis at Nodes 1 and 2. Simplify the analysis by calculating the transfer function for each of the signals with the other two signals set to zero. Then use superposition to obtain the overall transfer function. As shown in **Fig 2**, V_{IN2} and V_{IN1} are the differential-amplifier input signals ($V_{IN2}>V_{IN1}$). V_{REF} is the positive dc offset. For a sensor with a small zero-pressure offset and op amps powered from a single-ended supply, you may have to add a positive offset to keep the signal conditioner's own op amps from saturating near 0V.

First, with V_{REF} and V_{IN2} grounded, determine the transfer function for V_{IN1}.

At node 1:

$$(V_{IN1}/R_1)=V_O'-(V_{IN1}/R_2), \tag{1}$$

and at node 2:

$$(V_O'/R_3)=-(V_O/R_4). \tag{2}$$

Solving **Eqs 1** and **2** for V_O' and equating the results establishes **Eq 3**:

$$((R_2/R_1)+1)V_{IN1}=-(R_3/R_4)V_O. \tag{3}$$

Solving for V_O yields:

$$V_{O1}=-(R_4/R_3)((R_2/R_1)+1)V_{IN1},$$

where V_{O1} represents the part of V_O that V_{IN1} contributes.

To determine the transfer function for V_{IN2}, ground V_{IN1} and V_{REF} and use a similar analysis:

$$V_{O2}=((R_4/R_3)+1)V_{IN2},$$

where V_{O2} represents the part of V_O that V_{IN2} contributes.

Finally, to determine the transfer function from V_O to V_{REF}, ground V_{IN1} and V_{IN2} to obtain:

$$V_{OREF}=(R_4R_2/R_3R_1)V_{REF},$$

where V_{OREF} represents the part of V_O that V_{REF} contributes.

Adding the contributions of V_{IN1}, V_{IN2}, and V_{REF} gives the overall transfer function for the stage.

$$V_O=V_{O1}+V_{O2}+V_{OREF}.$$

$$V_O=-(R_4/R_3)((R_2/R_1)+1)V_{IN1}+((R_4/R_3)+1)V_{IN2}+(R_4R_2/R_3R_1)V_{REF}. \tag{4}$$

Eq 4 is the signal-conditioning stage's generalized transfer function. Not only is **Eq 4** cumbersome, but it also describes a circuit whose CMRR is poor unless you carefully control critical resistance ratios. If you control those ratios, the CMRR is excellent, and the transfer function becomes simpler because you can express some of the critical resistances as multiples of others. The simplified transfer function derived in the following paragraphs applies to a signal conditioner for pressure sensors.

Application to pressure-sensor circuits

For pressure sensors, V_{IN1} and V_{IN2} are referred to as S^- and S^+, respectively. The simplification is obtained by setting

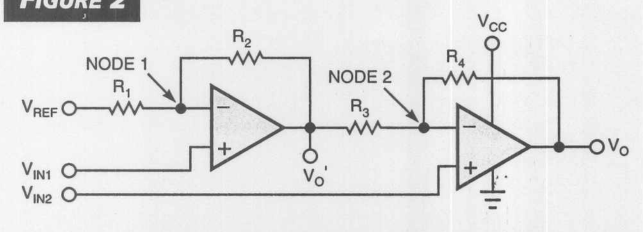
$$(R_4/R_3)=(R_1/R_2).$$

Through this simplification, **Eq 4** becomes:

$$V_O=((R_4/R_3)+1)(S^+-S^-)+V_{REF}. \tag{5}$$

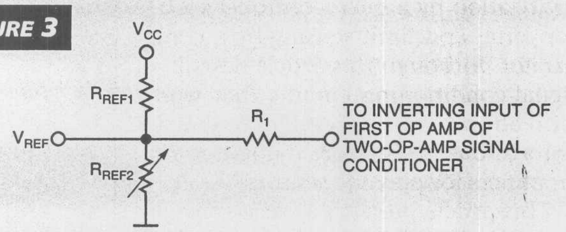
By examining **Eq 5**, the differential gain of the signal-con-

FIGURE 2



Choose the resistor values correctly, and this two-op-amp circuit behaves as an instrumentation amplifier, a circuit that many people think requires three op amps.

FIGURE 3



This simple resistive divider establishes an offset voltage, V_{REF}.

ditioning stage is:

$$G=(R_4/R_3)+1. \qquad (6)$$

Also, because the differential voltage between S^+ and S^- is the pressure sensor's actual differential output voltage (V_{SENSOR}), you obtain the following equation for V_O:

$$V_O=((R_4/R_3)+1)V_{SENSOR}+V_{REF}. \qquad (7)$$

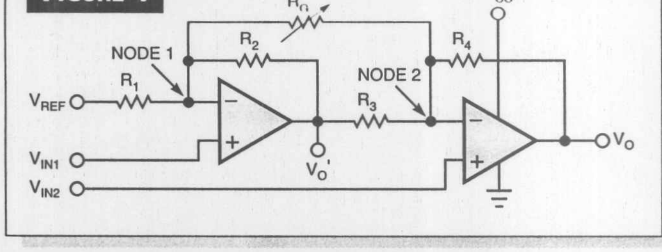
Finally, the term V_{REF} is the positive offset voltage added to the amplified sensor-output voltage. When you use a positive single-ended supply, V_{REF} must be positive. With this offset (dc level shift), you can adjust the absolute range that the sensor voltage spans. For example, if the gain established by R_4 and R_3 creates a span of 4V and you add an offset of 0.5V, the signal range becomes 0.5 to 4.5V.

A resistor divider usually adjusts V_{REF} (**Fig 3**). A few design constraints apply when you design this divider:

- To establish a stable positive offset (V_{REF}), regulate V_{CC}; otherwise, V_{REF} varies as V_{CC} varies.
- When you look into the divider from R_1, the effective resistance of the parallel combination of R_{REF1} and R_{REF2} should be at least an order of magnitude smaller than R_1. If the parallel combination's resistance is not small compared with R_1, R_1 depends on the parallel combination's resistance. This affects the amplifier's gain and reduces its CMRR.

You may need to vary the gain of the two-op-amp stage to fine-tune the span of the sensor's signal-conditioned output. Adjusting the gain without affecting the CMRR requires varying two resistors, however. If you could adjust the gain with one resistor, the circuit would be easier to work with. Adding R_G accomplishes this (**Fig 4**).

FIGURE 4



You can adjust the gain of the two-op-amp signal conditioner by varying a single added resistor.

As with the two-op-amp gain stage, deriving the general transfer function for the variable-gain stage involves nodal analysis and superposition.

$$V_O=((R_4/R_3)+(R_4/R_G)+(R_2R_4/R_3R_G)+1)V_{IN2}-((R_4/R_3)+(R_4/R_G)+(R_2R_4/R_3R_G)+(R_2R_4/R_1R_3))V_{IN1}+(R_2R_4/R_1R_3)V_{REF}.$$

This general transfer function is quite cumbersome. Moreover, without additional constraints on the resistor values, the circuit can provide unacceptable CMRR. To obtain good CMRR, simplify the expression in a similar fashion as before by setting

$$R_1=R_4$$

and

$$R_2=R_3.$$

Defining the voltage differential between V_{IN2} and V_{IN1} as V_{SENSOR}, the simplified transfer function is:

$$V_O=((R_4/R_3)+(2R_4/R_G)+1)(V_{SENSOR})+V_{REF}.$$

Thus, the gain is:

$$G=(R_4/R_3)+(2R_4/R_G)+1,$$

and V_{REF} is the positive dc level shift (offset).

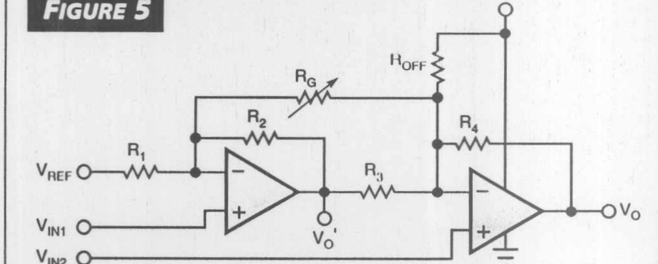
Use the following guidelines for determining the value for R_G:

- From the gain equation, R_G should be comparable to R_4. This allows fine-tuning of the gain established by R_4 and R_3. If R_G is too large, it has a negligible effect on the gain. If R_G is too small, it dominates the gain expression and prohibits fine gain adjustment.
- The R_G potentiometer should have a maximum resistance roughly equal to R_4. If you prefer to use a fixed resistor, use the potentiometer to adjust the gain, measure the potentiometer's resistance, and replace it with the closest 1% resistor.
- To maintain good CMRR while varying the gain, R_G should be the only resistor that varies. R_G equally modifies both of the resistor ratios that affect CMRR.

The final two-op-amp circuits incorporate a negative-offset capability, which is useful when the sensor's zero-pressure offset voltage is too high. An additional resistor, R_{OFF}, provides the offset (**Fig 5**). To derive the general transfer function, use nodal analysis and superposition:

$$V_O=(R_4/R_3)+(R_4/R_G)+(R_2R_4/R_3R_G)+1)V_{IN2}-(R_4/R_3)+(R_4/R_G)+(R_2R_4/R_1R_3)+(R_2R_4/R_3R_G)V_{IN1}+(R_2R_4/R_1R_3)V_{REF}+(R_4/R_{OFF})(V_{IN2}-V_{CC}).$$

FIGURE 5



Another added resistor injects a negative offset into the two-op-amp circuit, even though the circuit operates from a single positive power supply.

As before, defining the sensor's differential output as V_{SENSOR}, defining V_{IN2} as S^+ for pressure-sensor applications, and using the simplification

$$R_1=R_4$$

and

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$$R_2=R_3,$$

yields the following simplified transfer function:

$$V_O=(R_4/R_3)+(2R_4/R_G)+1)(V_{SENSOR})+V_{REF}+(R_4/R_{OFF})(S^+-V_{CC}).$$

The gain is:

$$G=(R_4/R_3)+(2R_4/R_G)+10. \qquad (8)$$

To adjust the gain, refer to the guidelines presented for the two-op-amp gain stage with variable gain. V_{REF} is the positive offset. The negative offset is:

$$V_{-SHIFT}=(R_4/R_{OFF})(S^+-V_{CC}).$$

The following guidelines help in designing the circuitry that introduces the negative offset.

- To establish a stable negative offset, regulate V_{CC}; otherwise, the amount of offset varies as V_{CC} varies.
- R_{OFF} should be the only resistor you vary to adjust the offset. Don't vary R_4. Doing so changes the gain of the two-op-amp circuit and reduces the CMRR.

To determine the value of R_{OFF}:

- Determine the required offset (V_{-SHIFT}).
- You should already have determined R_4 to set the gain for the desired output.
- Although V_{-SHIFT} depends on S^+, S^+ changes only slightly over the entire pressure range. With Motorola's MPX10 powered from a 5V supply, S^+ equals approximately 2.51V at zero pressure and increases to 2.53V at full-scale pressure. This variation over the full pressure span is negligible when you realize that many applications use 8-bit ADCs. With an 8-bit ADC, the 20-mV (0.02V) output change corresponds to only one count (0.39%) over the entire pressure range.
- Use the following equation to calculate R_{OFF}:

$$R_{OFF}=(S^+-V_{CC}/V_{-SHIFT})R_4.$$

An alternative is to use a potentiometer for R_{OFF}. Choose one whose resistance is from one to five times R_4). Fine-tune the negative offset while monitoring the zero-pressure output voltage, V_O. If you prefer a fixed resistor, measure the potentiometer's resistance and substitute the closest 1% resistor.

The CMRR of this circuit is low and may be unacceptable in some applications. (A Spice model exhibited a CMRR of only 28 dB.) This circuit works in applications in which only two operational amplifiers are available and the CMRR is not critical. The circuit may be the best choice when only two op amps are available, however. If you can add a third op amp, **Fig 6**'s circuit offers much better CMRR.

Another circuit adds a third op amp to the output of the two-op-amp gain block (**Fig 6**). This op amp has a dual function:

- Its noninverting configuration provides gain determined by R_6 and R_5.
- It can introduce a negative offset, usually via a resistor divider at V_{-SHIFT}.

Unlike the two-op-amp circuit, this circuit suffers neither intrinsic errors nor low CMRR when you introduce negative offsets. Therefore, when the required accuracy is high, this configuration can be superior.

The transfer function for three-op-amp stage is similar to that of the two-op-amp stage within it. Additional terms account for the negative offset and gain. As an example, if the stage uses the variable-gain two-op-amp circuit, all of the simpler circuit's design considerations and explanations apply.

Derive the transfer function by using nodal analysis and superposition.

$$V_O=(1+(R6/R5))((R_4/R_3)+(R_4/R_G)+ (R_2R_4/R_3R_G)+1)V_{IN2}-((R_4/R_3)+(R_4/R_G)+ (R_2R_4/R_3R_G)+(R_2R_4/R_1R_3))V_{IN1}+ ((R_2R_4/R_1R_3))V_{REF}-(R_6/R_5)V_{-SHIFT}.$$

First, simplify as before; that is, set

$$R_1=R_4$$

and

$$R_2=R_3.$$

Defining the voltage differential between V_{IN2} and V_{IN1} as V_{SENSOR}, the simplified transfer function is:

$$V_O=(1+(R6/R5))((R_4/R_3)+ (2R_4/R_G)+1)(V_{SENSOR})+ V_{REF}-(R6/R5)V_{-SHIFT}. \qquad (9)$$

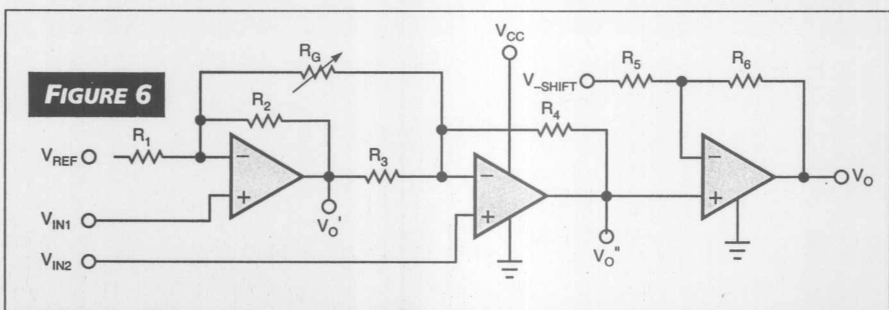
The gain is:

$$G=(1+(R6/R5))((R_4/R_3)+(2R_4/R_G)+1).$$

V_{REF} is the positive dc-level shift (offset), and V_{-SHIFT} is the negative dc-level shift.

In **Eq 9**, the third op-amp's gain also amplifies the positive and negative offsets, V_{REF} and V_{-SHIFT}. If you choose R_6 and R_5 to provide an arbitrary gain, designing appropriate offsets can be difficult. To simplify the transfer function, set $R^5=R^6$. The following equation for V_O results:

FIGURE 6



You can also introduce a negative offset by adding a third op amp at the output of the two-op-amp signal conditioner.

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$$V_O=2(((R_4/R_3)+(2R_4/R_G)+1)(V_{SENSOR})+V_{REF})-V_{-SHIFT}. \quad (10)$$

The third op amp's contribution to the overall system gain is 2. In designing the overall system gain and the positive offset, use the following guidelines:

- Because the third op amp contributes a gain of 2, choose the gain of the two-op-amp circuit to equal half the desired system gain. **Eq 8** gives the gain of the two-op-amp circuit.
- Because the third op amp amplifies V_{REF} by 2 (**Eq 10**), the resistor divider that generates V_{REF} should provide half the positive offset required at the output.
- Because $R_5=R_6$, the negative offset, V_{-SHIFT}, which is also created by a voltage divider, is now amplified by a factor of 1. Again, apply the constraints you used to design the voltage divider in the pressure-sensor circuits.

Although the discussion centers on pressure-sensor applications, you can use these amplifier circuits with almost any differential-voltage-output sensor. The circuits exhibit high input impedance, low output impedance, high gain capability, and differential-to-single-ended conversion. Each amplifier circuit allows positive dc offsets; the last two can also provide negative offsets. This article details a method of using an additional feedback resistor to adjust the differential voltage gain without sacrificing CMRR. With adjustable offset and variable gain, you can match a sensor's conditioned output to the input range of the circuits that follow. Combining sensors and amplifiers provides a versatile system solution in applications for which no ideal fully signal-conditioned sensor exists or in which you need more flexibility than such sensors provide. EDN

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